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Comprehensive Robustness Analysis of GCM, CCM, and OCB3

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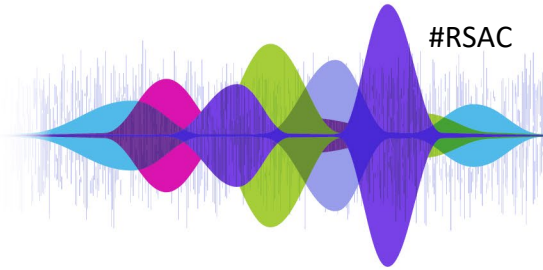

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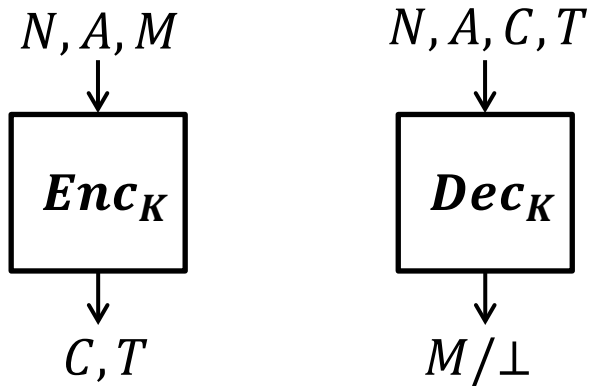
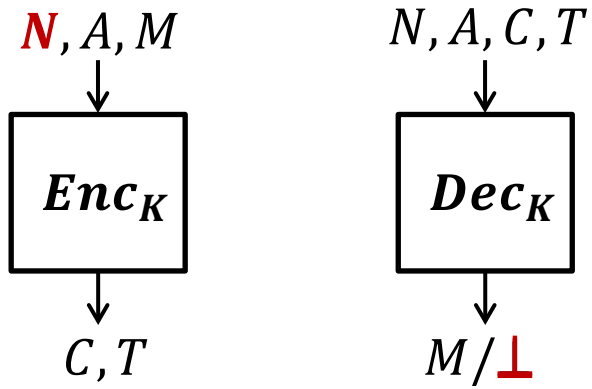
Authenticated encryption; AE

- Symmetric-key crypto to provide privacy (priv) & authenticity (auth)
- Widely deployed in real-world protocols, e.g., TLS, WPA
- Encryption: $Enc_K(N, A, M) = (C, T)$
  - K: key, N: nonce, A: associated data (AD), M: plaintext, C: ciphertext, T: tag
- Decryption: $Dec_K(N, A, C, T) = M$ when inputs are authentic; Otherwise, outputs $\perp$



Misuse of AE

- When using AE, there are some rules we must follow; e.g.,
  - **Nonce respecting**
    .. The user cannot input the same nonce twice in Enc_K.
  - **Decryption respecting**
    .. Dec_K is not allowed to output other than ⊥ if inputs are not authentic.
- If breaking those rules (= **misusing AE**), priv & auth of AE can be broken.
  - e.g., GCM reveals auth key when nonces are misused. [Jou06]



Real-world attack

- Bock et al. investigate the real-world cases in TLS that use **GCM in a nonce-misuse setting**. [BZD+16]
  - Several TLS implementations are vulnerable to forgery attacks.
  - + 70,000 HTTPS servers are also potentially vulnerable due to the use of GCM with **random nonce of short length**.
- Padding oracle attack [Vau02]
  - **Dec leaks info on the decrypted plaintext.**
- Efail attack [PDM+18]
  - Mail server decrypts maliciously manipulated ciphertext and executes the code inside **without verification**.

Nonce-misuse security

- Nonce-Misuse **Resistance** (**NMR**) [RS06]
  - Possible strongest security under nonce misuse;
    No matter how much nonces are misused, priv / auth is maintained.
- Nonce-Misuse **resiLience** (**NML**) [ADL17]
  - Relaxation of NMR; Even if some nonces are misused,
    priv / auth is maintained as long as new nonces are used.
- Tradeoff between security strength and efficiency
  - NMR-secure AE is at most rate-1/2, while NML-secure AE can be rate-1.
  - Rate: measurement of AE efficiency; # processing blocks per 1 E_K call

Decryption-misuse security

- Security under Release of Unverified Plaintext (**RUP**) [ABL+14]
  - Dec function outputs decrypted plaintext **regardless of verification**
  - Priv: plaintext awareness (PA1/PA2)
  - Auth: integrity under RUP (INT-RUP)

Previous work on misuse security of AE

- In the previous AE competitions,
  misuse security is one of the central topics.
  - CAESAR
    - Attack: OCB3 (PA1, INT-RUP), COPA (PA1, INT-RUP)
    - Proof: Minalpher (INT-RUP), AEZ (NMR, RUP), Deoxys-II (NMR)
  - NIST lightweight cryptography
    - Proof: Elephant (NMR-Auth), GIFT-COFB (NML-Priv, NML-Auth),
      Romulus-N (NML-Priv, NML-Auth),
      Romulus-M (NMR-Priv, NMR-Auth, PA1, NMR-INT-RUP)

Research question

- **What about misuse security of the standard AEs?**
  - Vaudenay and Vizár [VV18] show a comprehensive **NMR** comparison of 3rd candidates of CAESAR, plus GCM and CCM.
- There is room for deep analysis, such as **NML** and **RUP**.
- It is important to clarify misuse security of standards since they are *standard* and should be the baseline of AE.
- We pick up GCM, CCM, OCB3, ChaCha20-Poly1305 as standards.

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NIST standards RFC standards

Contribution

- **Some missing / questionable cases on GCM, CCM, and OCB3**

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	?	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
CCM	✗ [ABL+14]	?	✗ [VV18]	?	?	?
OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘? [ADL17]	✘? [ADL17]
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [KDDI17]	✓ [ADL17]	✓ [ADL17]

* GCM is NML-Priv secure only when 96-bit nonce.

Contribution

- **We can prove security in all these missing / questionable cases!**

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
CCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	? ⇒ ✔	? ⇒ ✔	? ⇒ ✔
OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘ ? ⇒ ✔	✘ ? ⇒ ✔†
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [KDDI17]	✓ [ADL17]	✓ [ADL17]

* GCM is NML-Priv secure only when 96-bit nonce.
† OCB3 is NML-Auth secure only when AD is empty.

GCM: NIST SP800-38D

- INT-RUP was unknown despite GCM has been extensively studied.
- GCM was considered vulnerable in any misuse scenario.
- Our result shows that this is not the case!

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
CCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	? ⇒ ✔	? ⇒ ✔	? ⇒ ✔
OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘ ? ⇒ ✔	✘ ? ⇒ ✔†
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [KDDI17]	✓ [ADL17]	✓ [ADL17]

OCB3: RFC 7253

- Ashur et al. proposed NML-Priv & NML-Auth attacks against **OCB1**.
- They claim, "**We focus on OCB version 1, however our results extend to all versions of OCB.**"

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
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OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘ ? ⇒ ✔	✘ ? ⇒ ✔†
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [KDDI17]	✓ [ADL17]	✓ [ADL17]

OCB3: RFC 7253

- We show their attacks are **not** applicable to OCB3, and we can prove both security.
- Note: AD needs to be empty for NML-Auth.

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
CCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	? ⇒ ✔	? ⇒ ✔	? ⇒ ✔
OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘ ? ⇒ ✔	✘ ? ⇒ ✔†
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [KDDI17]	✓ [ADL17]	✓ [ADL17]

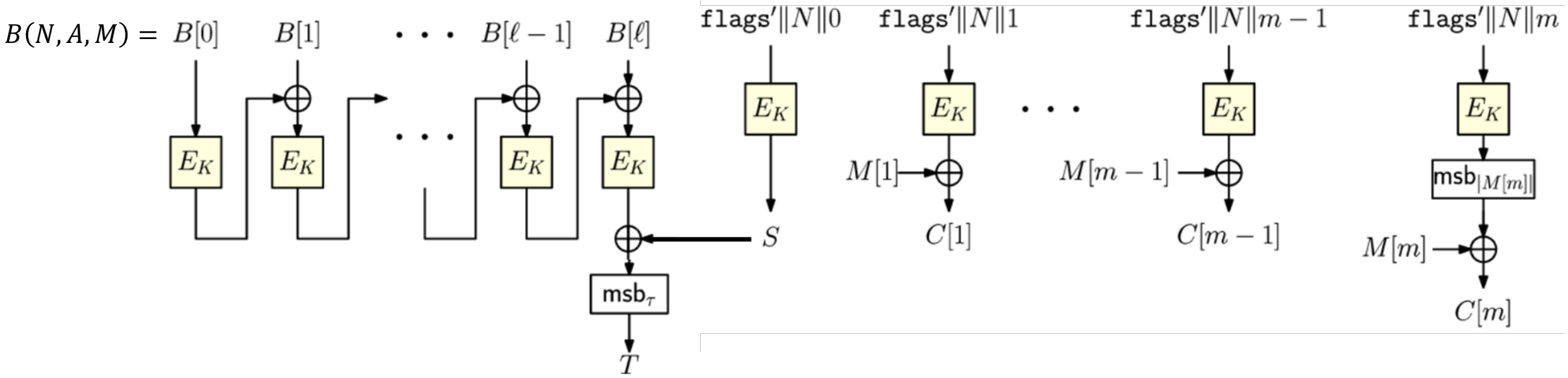
CCM: NIST SP 800-38C

- Only few works on provable security exist.
- Previous research only revealed trivial cases.
- In this talk, we give details of these results.

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
CCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	? ⇒ ✔	? ⇒ ✔	? ⇒ ✔
OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘ ? ⇒ ✔	✘ ? ⇒ ✔†
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [KDDI17]	✓ [ADL17]	✓ [ADL17]

CCM

- MAC-then-Enc: CBC-MAC + CTR
  - CBC-MAC output is XORed with encryption of nonce & zero.
  - Input of CBC-MAC: encoded string $B(N, A, M) = B[0] \,||\, B[1] \,||\, \cdots \,||\, B[\ell]$
  - $B(N, A, M)$ is **prefix-free**:
    there is no $B(\cdot,\cdot,\cdot)$ corresponding to the prefix of other $B(\cdot,\cdot,\cdot)$.



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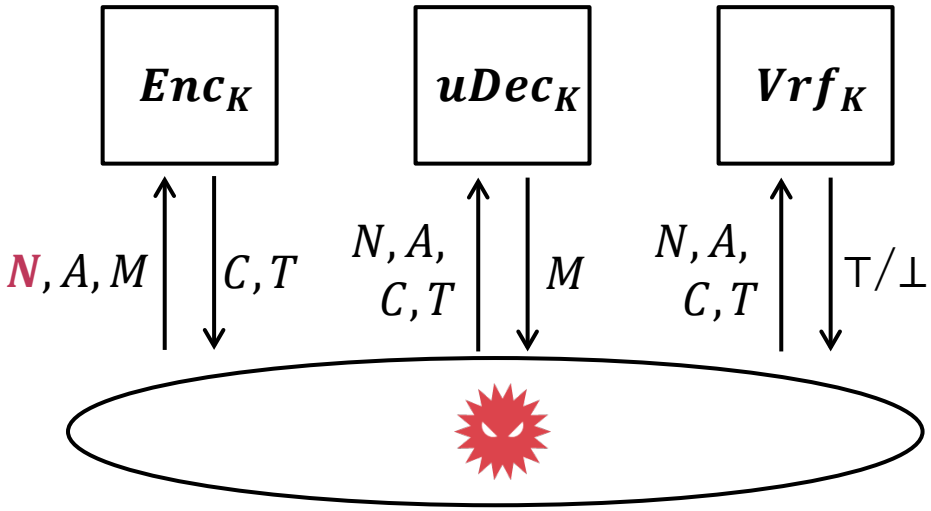
  - $B(N, A, M)$ is **prefix-free**:
    there is no $B(\cdot,\cdot,\cdot)$ corresponding to the prefix of other $B(\cdot,\cdot,\cdot)$.
- Existing misuse security analysis
  - Fouque et al. [FMVZ08], Vaudenay and Vizár [VV18]: NMR-Auth attack
    - Comp: $O\left(2^{n/2}\right)$, where n is block size
  - Other than these results, as far as we investigated,
    no results on misuse security of CCM.

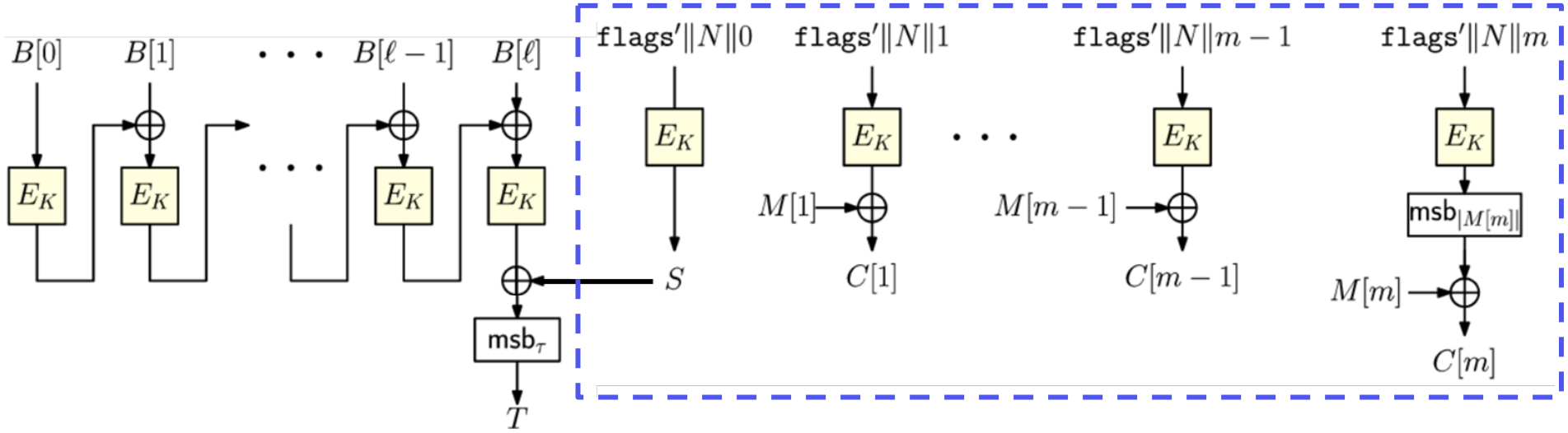
Misuse auth on CCM

- **We show CCM has NMR-INT-RUP security.**
  - NMR-INT-RUP implies all missing misuse auth on CCM: INT-RUP, NMR-Auth, NML-Auth.
- Separated syntax
  - $Enc_K(N, A, M) = (C, T)$,
  - $uDec_K(N, A, C, T) = \boldsymbol{M}$,
  - $Vrf_K(N, A, C, T) = \top/\bot$
- NMR-INT-RUP
  - Prob. of forging under Enc, $uDec$, Vrf queries
  - Nonce can be repeated even in Enc_K



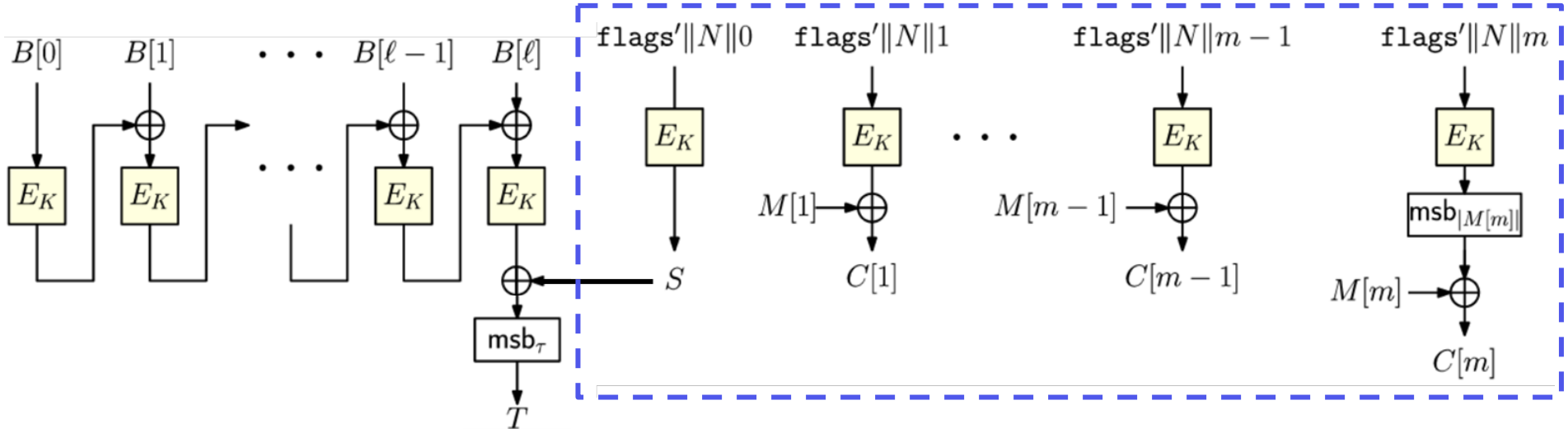
Proof overview

- Reduce NMR-INT-RUP of CCM to a variant of UF-CMA of CBC-MAC.
  - UF-CMA: unforgeability under chosen message attacks
  - Define UF-CMA+: UF-CMA with additional accesses to [ ].
- CBC-MAC is secure if the input is prefix-free [PR97].
  - Recall: CBC-MAC input in CCM is prefix-free; this holds even if nonce misuse.
  - **We can prove security of CBC-MAC under UF-CMA+ as well!**



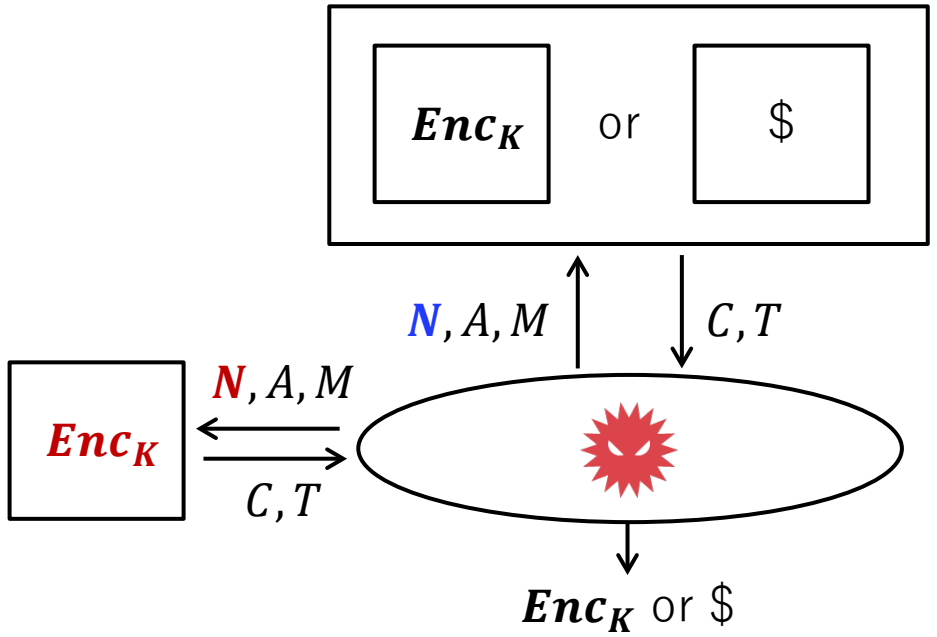
Security bound

- Prove UF-CMA+ of CBC-MAC by H-coefficient.
  - Bad events: collision at E_K input
- We show that CCM has NMR-INT-RUP security of $\boldsymbol{O\left(\min\left\{2^{n/2}, 2^{\tau}\right\}\right)}$
  - n: block size, τ: tag length
  - **Same security level as standard auth**



Misuse priv on CCM

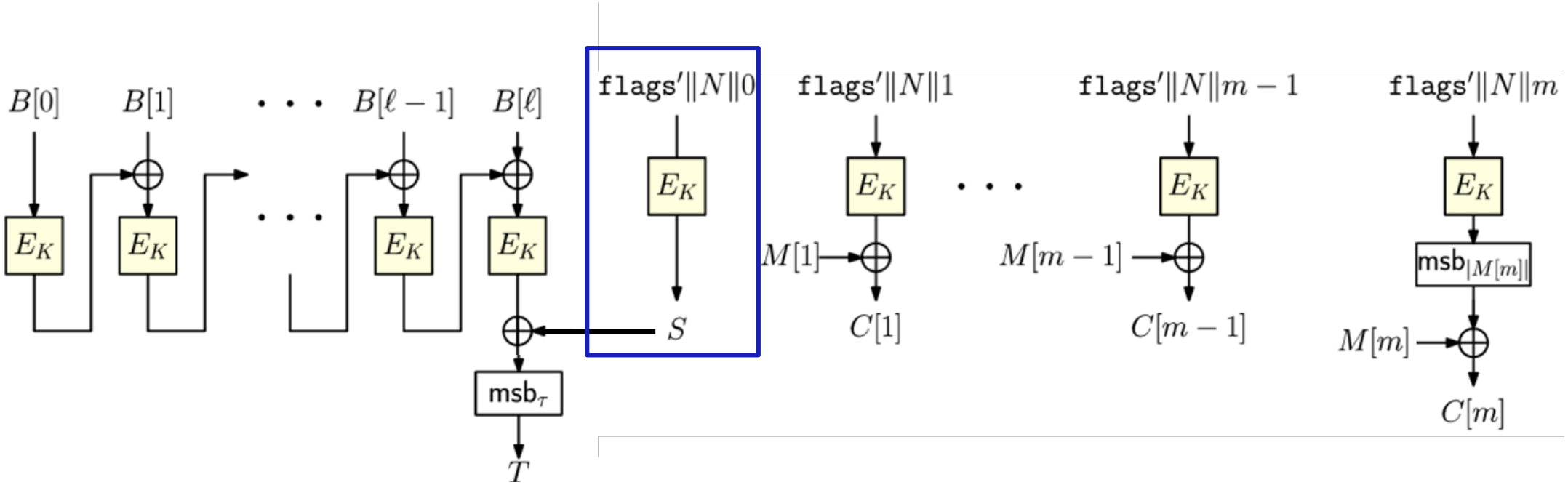
- CCM has NMR-Auth, but does not have NMR-Priv.
  - Encryption of CCM is CTR
  - Same nonces produce same key streams.
- What about NML-Priv?
  - Def: Prob. of distinguishing $\boldsymbol{Enc_K}$ from \$ with **nonce-respecting queries** under **nonce-repeating queries** to $\boldsymbol{Enc_K}$



- We can prove CCM has NML-Priv of $\boldsymbol{O(2^{n/2})}$.
  - Even if some nonces are misused, the adv. cannot violate the security of the keystream derived from other non-misused nonces.

Optimization of CCM: CCM2

- CCM2 omits the mask generation for the tag (▭) in CCM.
- CCM2 reduces 1 E_k call &
  achieves the same misuse security as CCM.
  - NMR-INT-RUP & NML-Priv



Performance of CCM2: short-input case

- Adomnicăi et al. [AMS23] show that general-purpose AE require at least 3 E_K calls to process non-empty input.
- CCM2 achieves this minimum number, which implies excellent performance for very short inputs, e.g., on microcontrollers.

	GCM*	CCM	OCB3	COFB	**CCM2**
E_K Calls	3 + 2 mul	4	4	3	**3**
Parallel-lizability	3 + 1 mul + 1 mul	2+2	2+2	1+1+1	**2+1**

* When using 96-bit nonce

Lessons learned

- When using AE, please check its rules and follow them.
- Using misuse-resistant AE is good choice … but,
- There is a tradeoff between security strength and efficiency.
- It is important to select AE that are suitable to your environment, & check what happens if the rules of these AE are violated.
  - If you consider using GCM, CCM, OCB3, or ChaCha20-Poly1305, please check the summary table in our research 😉

Summary

- Provided a comprehensive overview on the misuse security of the following four standard AEs.
  - CCM & CCM2 have the strongest misuse strength among the four AEs.

	RUP		NMR		NML	
	PA1	INT-RUP	Priv	Auth	Priv	Auth
GCM	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	✗ [Jou06]	✓* [ADL17]	✗ [ADL17]
CCM/CCM2	✗ [ABL+14]	? ⇒ ✔	✗ [VV18]	? ⇒ ✔	? ⇒ ✔	? ⇒ ✔
OCB3	✗ [ABL+14]	✗ [ABL+14]	✗ [Classical]	✗ [VV18]	✘ ? ⇒ ✔	✘ ? ⇒ ✔†
ChaCha20-Poly1305	✗ [ABL+14]	✓ [IMI16, IMI18]	✗ [Classical]	✗ [II16]	✓ [ADL17]	✓ [ADL17]

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Reference & Appendix

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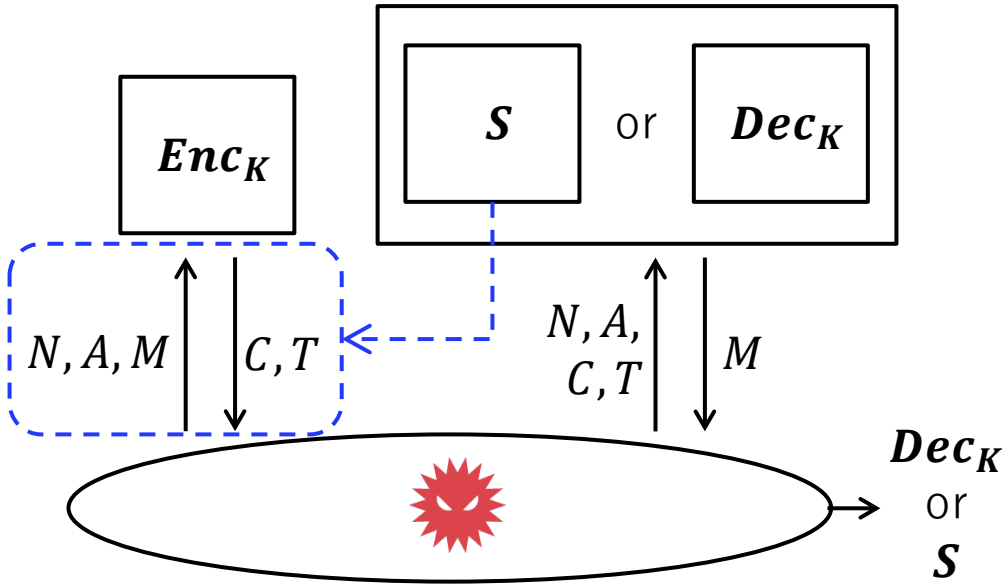
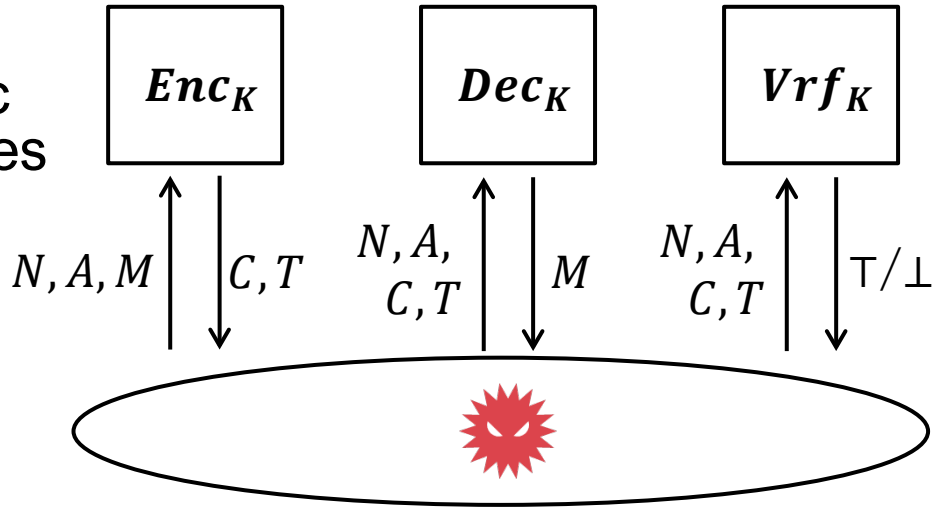
RUP: Definition

- Separated syntax:
  - $Enc_K(N, A, M) = (C, T)$,
  - $Dec_K(N, A, C, T) = M$,
  - $Vrf_K(N, A, C, T) = \top/\bot$



- Privacy: Plaintext awareness (PA1/2)
  - Prob. of distinguishing a simulator mimicking Dec without a key from genuine Dec under Enc queries



- Authenticity: Integrity under RUP (INT-RUP)
  - Prob. of forging under Enc, Dec, Vrf queries

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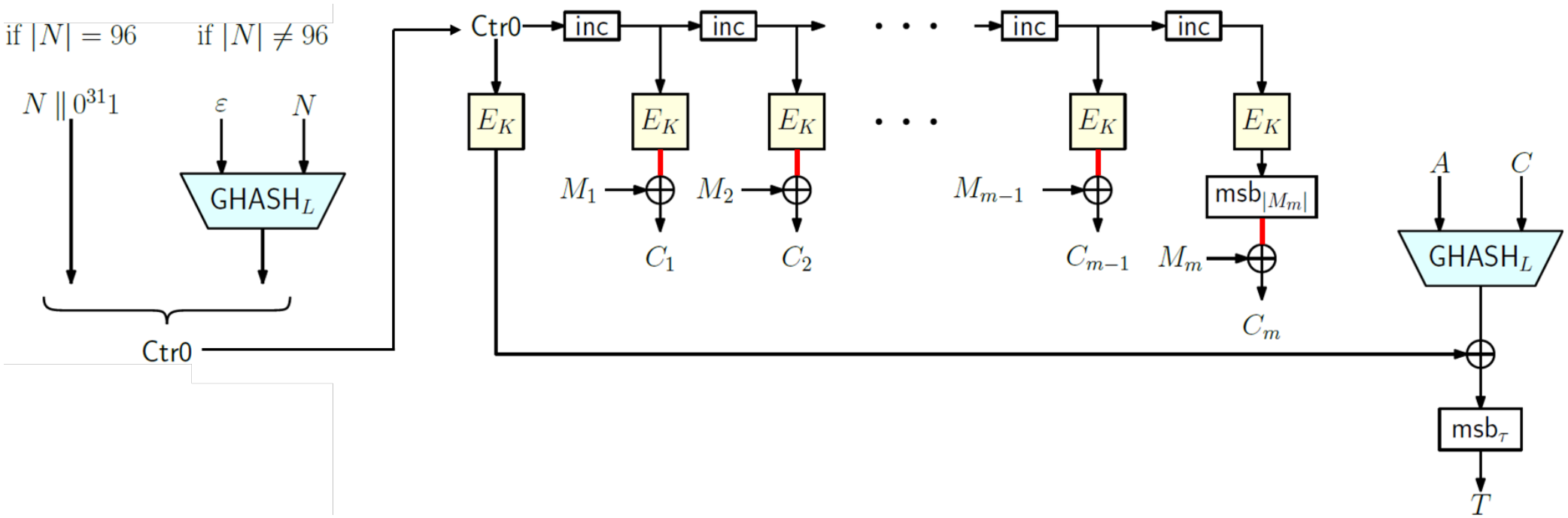
GCM INT-RUP proof: First observation

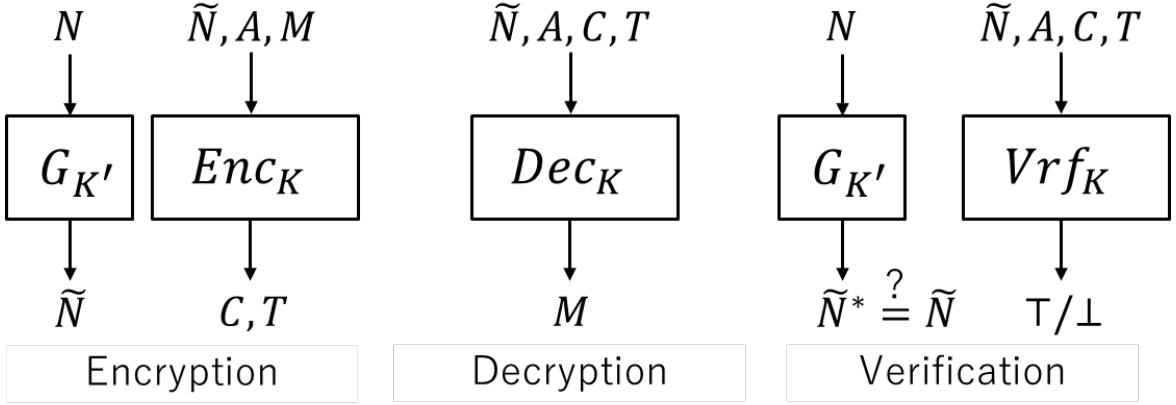
- Recall: the adversary can access to $Dec_K(N, A, C, T) = M$
  - Dec reveals only the **key stream** on the queried nonce.
  - If querying the same nonce as that in Enc queries, adv. can only obtain key stream and it cannot mount Joux's forbidden attack [Joux06].



Application of our result

- GCM is **not** PA1 secure. Does having “only” INT-RUP security make sense?
- One answer: Nonce decoy [ABL+14]
  - It converts a scheme into a PA1 one, **if the baseline scheme is PA1 under random IV.**
  - It encrypts an input nonce and outputs its value in addition to typical AE outputs.
  - (Recall) CTR is PA1 under random IV → **CTR (GCM) fulfills this requirement.**
  - **Nonce decoy preserves INT-RUP** of the baseline scheme.

→ **GCM can be converted to be RUP secure just applying nonce decoy!**



Enc_K, Dec_K, Vrf_K : Baseline AE

$G_{K'}$: PRF s.t. $G_{K'}: \{0,1\}^{|N|} \to \{0,1\}^{|N|}$

Output of enc: $(N, \widetilde{N}, A, C, T)$

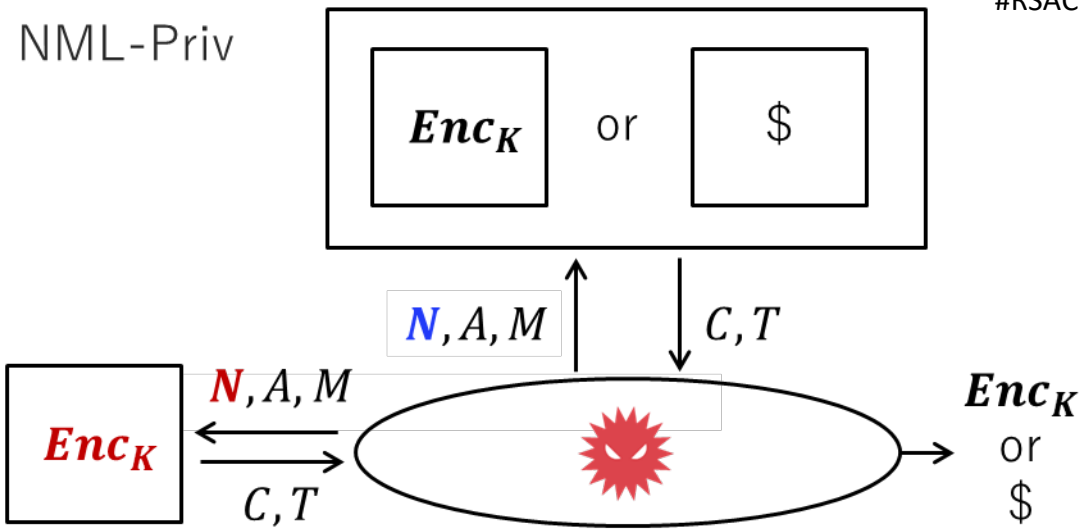
Comparison

- PRF-to-IV and GCM-RUP do not rely on INT-RUP security of GCM
- **GCM + Nonce decoy works well because GCM is INT-RUP**
  - 👍 RUP security, black box, comparable increase of computation, and low dec latency
  - 👎 Ciphertext expansion for an encrypted nonce

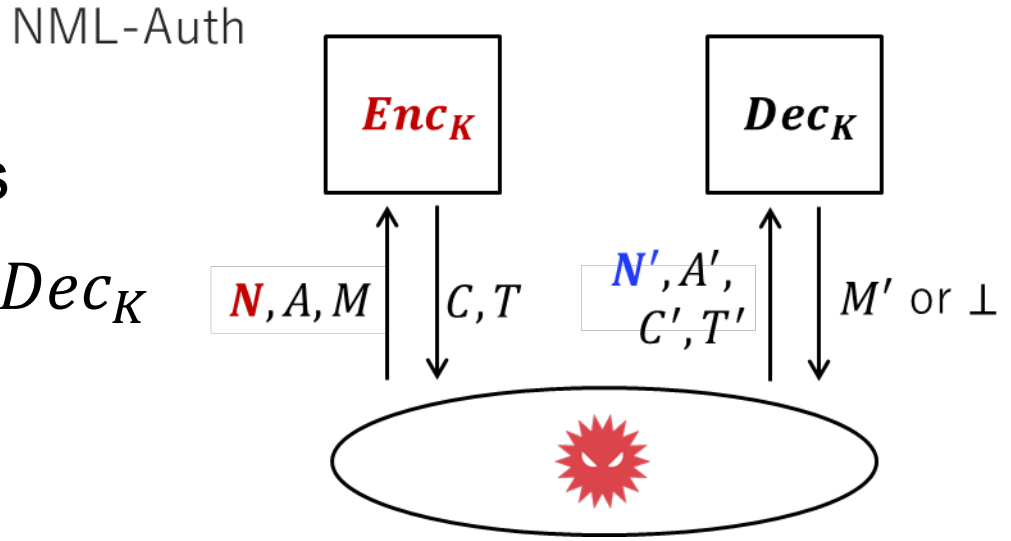
Scheme	Security: PA1 + INT-RUP	Black box conversion	Increase of computation	Dec latency (until dec part starts)	Ciphertext expansion
GCM + PRF-to-IV	○	○	PRF(N,A,M)	None	|N|
GCM-RUP	○	×	≤ 1 BC call	GHASH(A, C) + GHASH(N, ε)	None
GCM + Nonce decoy	○	○	1 BC call	None	|N|

NML-Auth

- Syntax:
  - $Enc_K(N, A, M) = (C, T)$,
  - $Dec_K(N, A, C, T) = M/\perp$



- NML-Auth
  - Prob. of forging under Enc, Dec queries
  - Nonce can be repeated both Enc_K and Dec_K
  - In Dec_K, adv. cannot use nonces which is repeated in Enc_K



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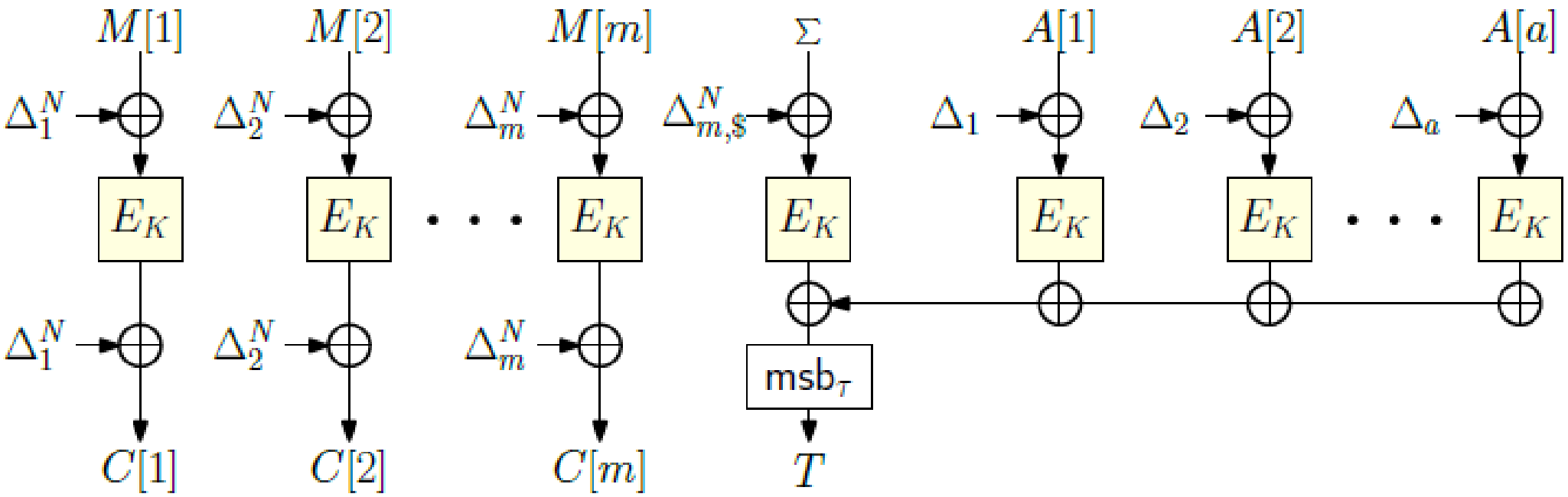
OCB3


$M[1]$
$M[2]$
$M[m]$
Σ
$A[1]$
$A[2]$
$A[a]$
Δ_1^N
Δ_2^N
Δ_m^N
$\Delta_{m,\$}^N$
Δ_1
Δ_2
Δ_a
E_K
msb_τ
$C[1]$
$C[2]$
$C[m]$
T

OCB1

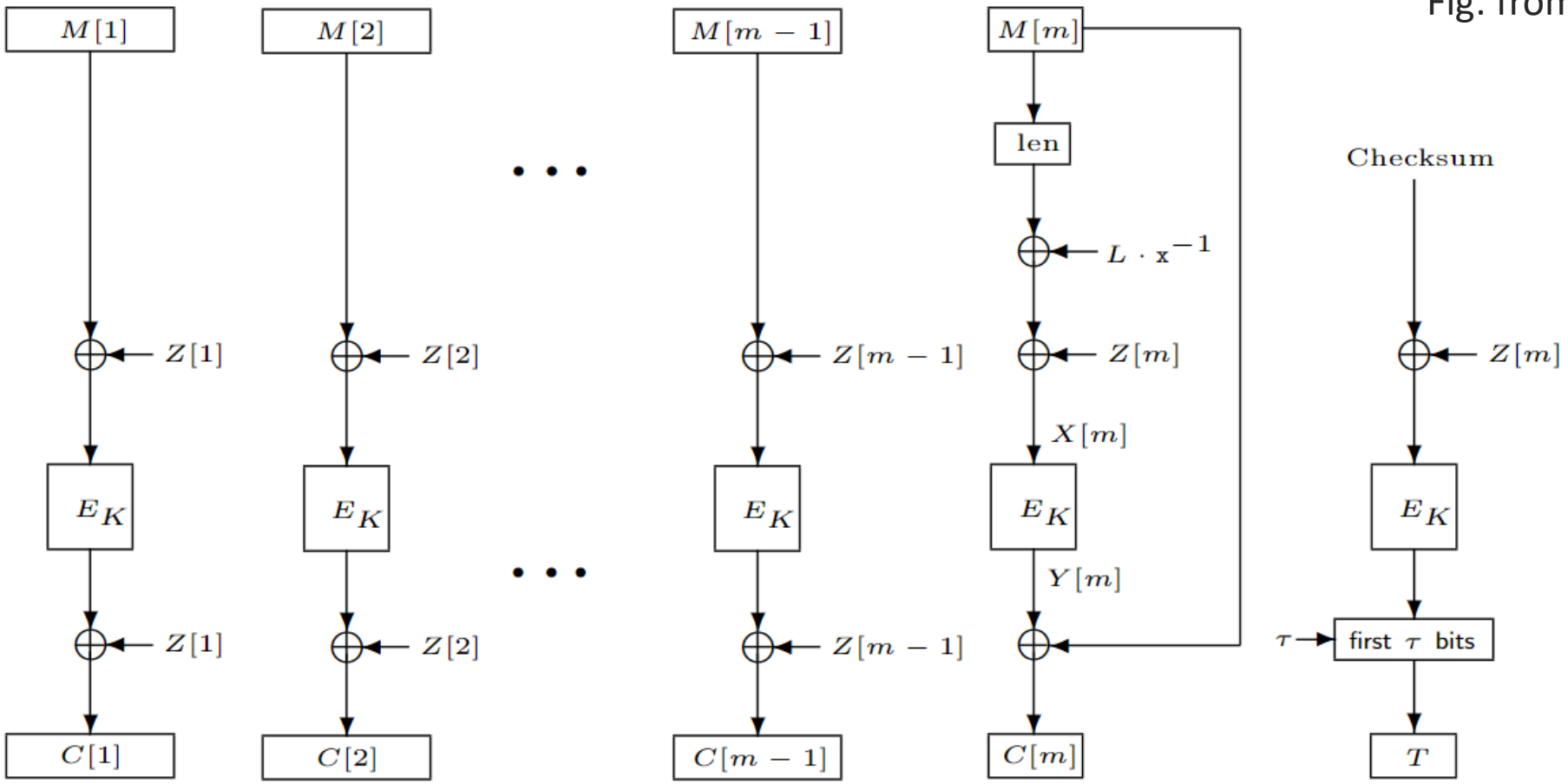


Fig: from [RBBK01]

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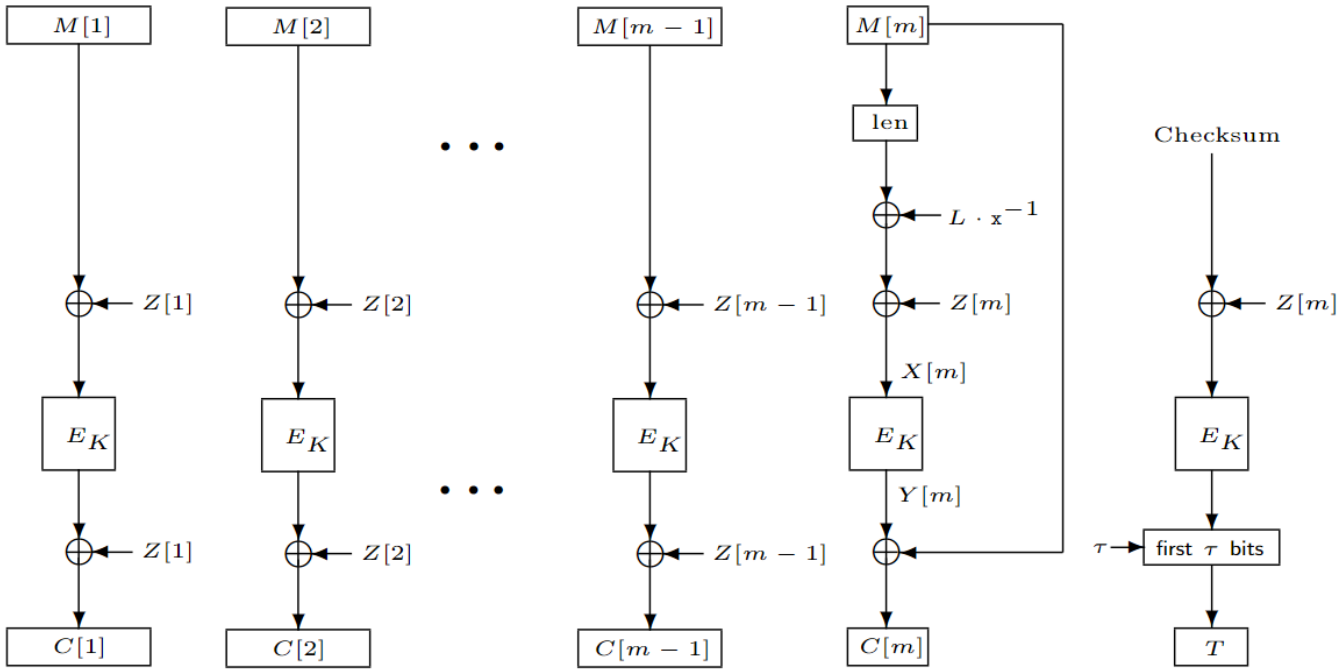
Overview of NML attacks on OCB1 [ADL17]

Fig: from [RBBK01]



- Spec. of OCB1
  - Masks are derived from two seeds.
    - $L = E_K(0^n), R = E_K(L \oplus N)$
  - OCB1 does **not** use a special mask for tag derivation XE.
    - We can use $Z[m]$ for both tag derivation and message processing.
- Attack Idea
  - Nonce-misuse queries with various lengths allow the adv. to query XE and XEX with the same nonce and index.
  - Adv. can recover the mask value, and by repeating this, it also can recover two mask seeds.
  - Once mask seeds are recovered, adv. can mount privacy and authenticity attacks against nonce-respecting queries.

NML analysis on OCB3

- We cannot apply the previous OCB1 attack to OCB3.
  - In OCB3, tag derivation XE uses a special mask, unlike OCB1.
  - Various length queries do not reveal the mask.
- We can prove NML-Priv.
  - Recall: security of OCB3: ΘCB sec. + XEX* sec.
  - XEX* sec.: no restriction on nonce repetition
    ⇒ It is enough to prove the NML-Priv of ΘCB.
  - We can prove it in the similar manner as the standard security proof of ΘCB.
- We can prove NML-Auth when AD is empty in the same manner as NML-Priv.
  - Why AD has to be empty?: AD processing is **not** nonce-based.
    ⇒ Two NM queries can reveal diff. of AD processing value as shown in [VV18].

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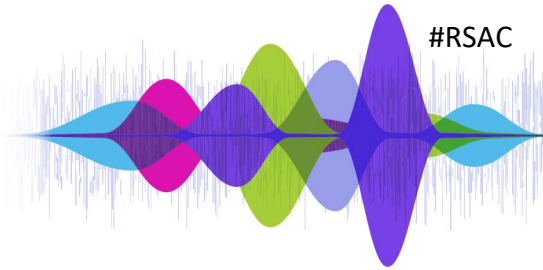
Many Voices.
One Community.

SESSION ID: CRYP-M02B

Meet-in-the-Middle Attack on Primitives with Binary Matrix Linear Layer

Kuntong Li

Masters Student
Shandong University



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Outline

- Background and preliminary
- New models for linear layer with binary matrix
- Key recovery attack on Midori64
- Preimage attack on weakened Camellia and Aria
- Conclusion

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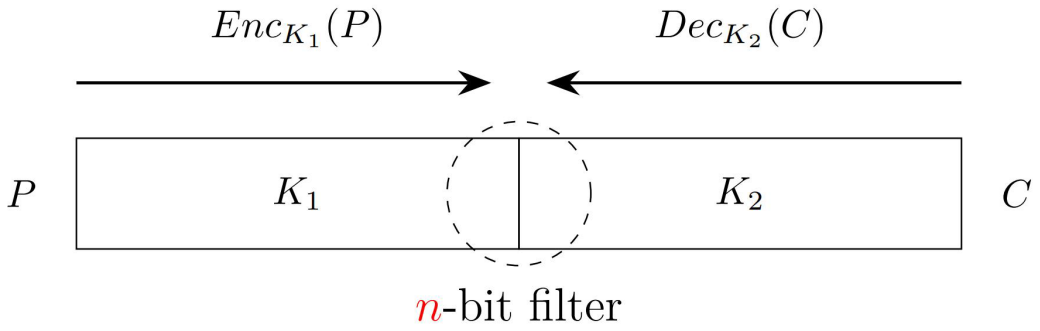
Background and preliminary

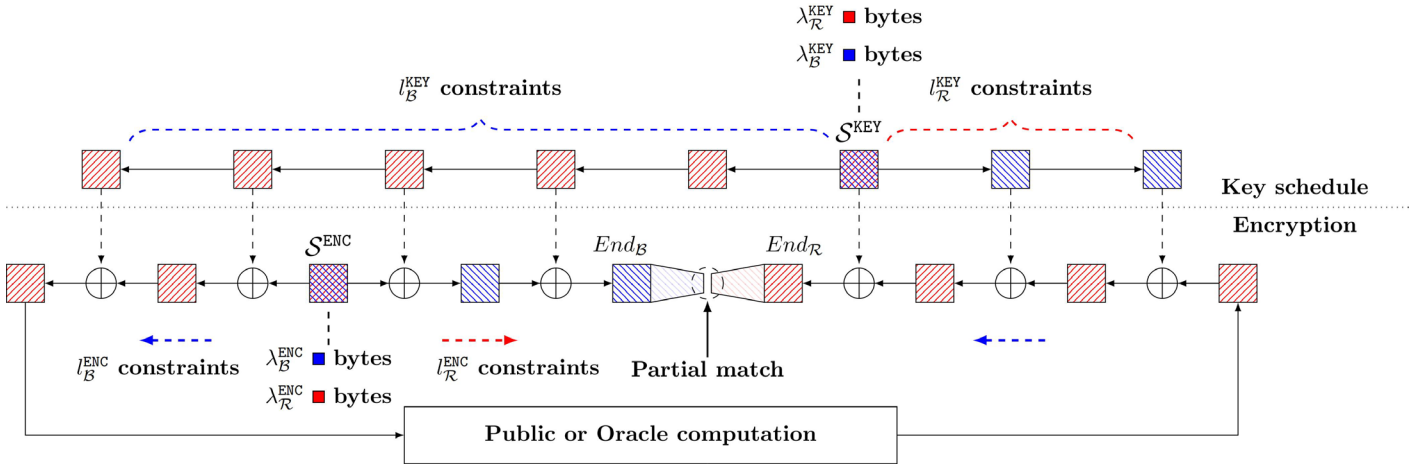
Meet-in-the-Middle(MitM) attack

Meet-in-the-Middle(MitM) attack was first introduced by Diffie and Hellman[DH77] in 1977.



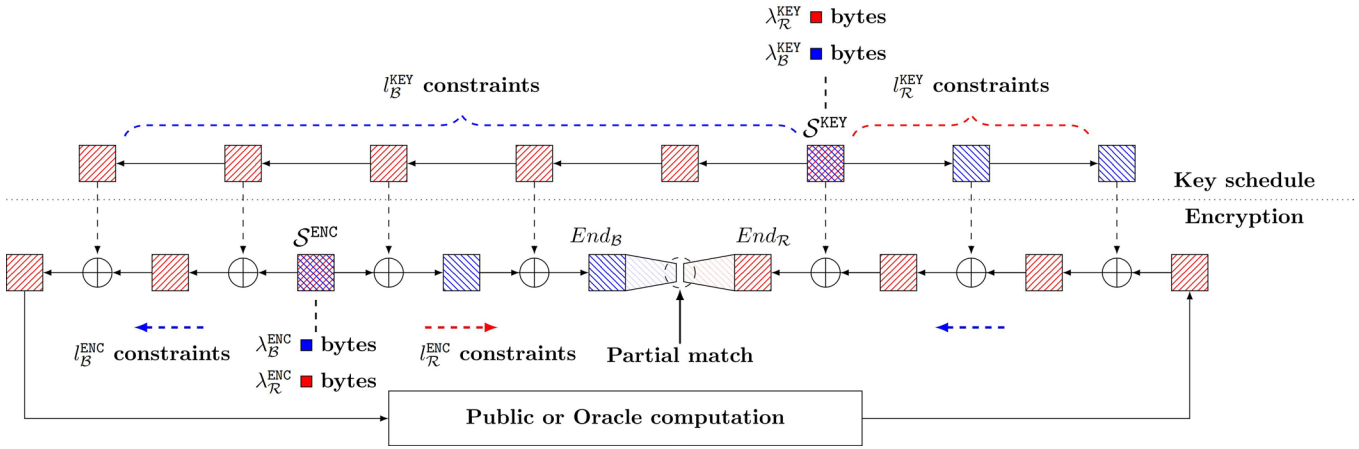
- Forward Encryption: store K_1 in table $L_1[Enc_{K_1}(P)]$.
- Backward Decryption: store K_2 in table $L_2[Dec_{K_2}(C)]$.
- Find match between L_1 and L_2.
- $2^{|K_1|+|K_2|-n} (< 2^{|K_1|+|K_2|})$ keys survived.

Framework of the Meet-in-the-Middle Attack



- MILP-based preimage attack [EC:BDG+21]
- Key-recovery and collision attacks, Table-based methods [C:DHSLWH21]
- Superposition (SupP) states, Bi-directional attribute propagation (BiDir) [C:BGST22]

Framework of the Meet-in-the-Middle Attack

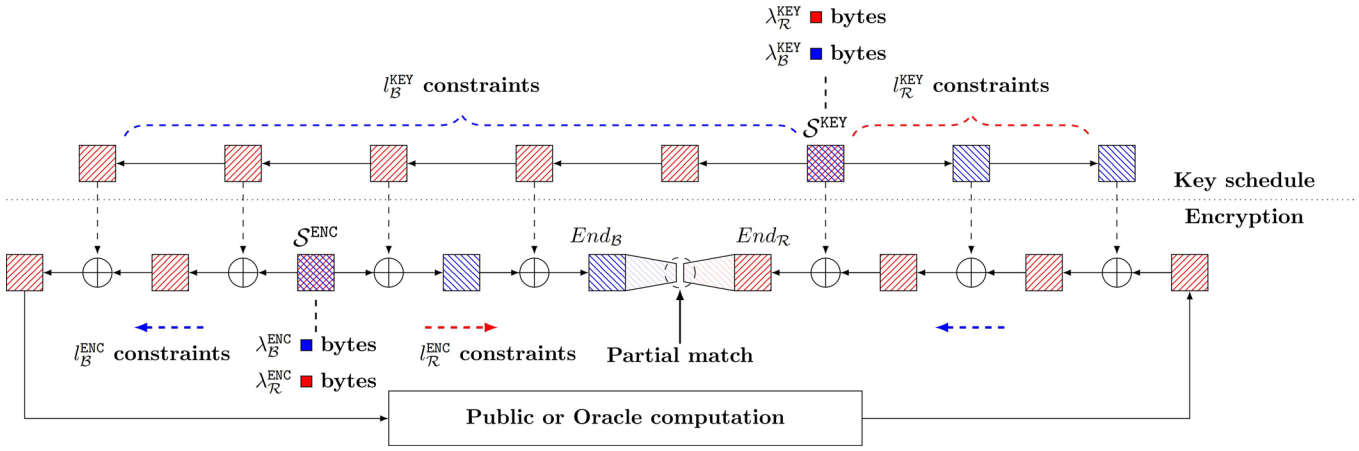


- Initial structure:

$$\begin{cases} \text{Starting states: } \mathcal{S}^{\mathtt{ENC}}, \mathcal{S}^{\mathtt{KEY}} \\ \lambda_{\mathcal{B}} \blacksquare,\ \lambda_{\mathcal{R}} \blacksquare,\ \lambda_{\mathcal{G}} \blacksquare \text{ in starting states.} \\ l_{\mathcal{B}} \text{ constraints on } \blacksquare,\ l_{\mathcal{R}} \text{ constraints on } \blacksquare. \end{cases}$$

- Forward: $\mathrm{DoF}_{\mathcal{B}} = \lambda_{\mathcal{B}} - l_{\mathcal{B}}$ values of $\blacksquare$.
- Backward: $\mathrm{DoF}_{\mathcal{R}} = \lambda_{\mathcal{R}} - l_{\mathcal{R}}$ values of $\blacksquare$.
- Match: DoM bytes from $End_{\mathcal{B}} = End_{\mathcal{R}}$.

Framework of the Meet-in-the-Middle Attack



- Initial structure:

$$\begin{cases} \text{Starting states: } \mathcal{S}^{\text{ENC}}, \mathcal{S}^{\text{KEY}} \\ \lambda_{\mathcal{B}} \blacksquare,\ \lambda_{\mathcal{R}} \blacksquare,\ \lambda_{\mathcal{G}} \blacksquare \text{ in starting states.} \\ l_{\mathcal{B}} \text{ constraints on } \blacksquare,\ l_{\mathcal{R}} \text{ constraints on } \blacksquare. \end{cases}$$

- Forward: $\text{DoF}_{\mathcal{B}} = \lambda_{\mathcal{B}} - l_{\mathcal{B}}$ values of $\blacksquare$.
- Backward: $\text{DoF}_{\mathcal{R}} = \lambda_{\mathcal{R}} - l_{\mathcal{R}}$ values of $\blacksquare$.
- Match: DoM bytes from $End_{\mathcal{B}} = End_{\mathcal{R}}$.

Attack Framework

1. Choose constants in $\mathcal{S}^{\text{ENC}}$ and $\mathcal{S}^{\text{KEY}}$ and $l_{\mathcal{B}}^{\text{ENC}} + l_{\mathcal{B}}^{\text{KEY}} + l_{\mathcal{R}}^{\text{ENC}} + l_{\mathcal{R}}^{\text{KEY}}$ constraints.
2. For $\text{DoF}_{\mathcal{B}}$ values of $\blacksquare$, compute to $End_{\mathcal{B}}$ and store them in $L_1[End_{\mathcal{B}}]$.
3. For $\text{DoF}_{\mathcal{R}}$ values of $\blacksquare$, compute to $End_{\mathcal{R}}$ and store them in $L_2[End_{\mathcal{R}}]$.
4. Find match between L_1 and L_2.
5. For the surviving pairs that pass the match, check for a full-state match.

Framework of the Meet-in-the-Middle Attack

Attack Framework

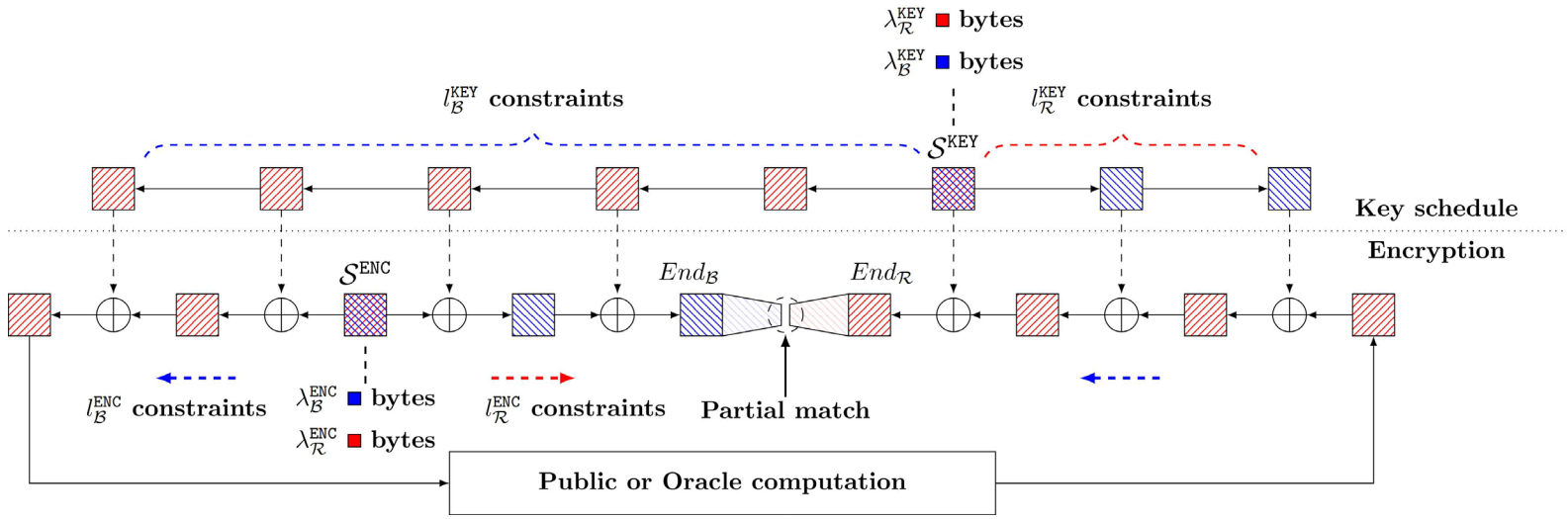
1. Choose constants in $\mathcal{S}^{\mathtt{ENC}}$ and $\mathcal{S}^{\mathtt{KEY}}$ and $l_{\mathcal{B}}^{\mathtt{ENC}} + l_{\mathcal{B}}^{\mathtt{KEY}} + l_{\mathcal{R}}^{\mathtt{ENC}} + l_{\mathcal{R}}^{\mathtt{KEY}}$ constraints.
2. For $\mathrm{DoF}_{\mathcal{B}}$ values of ■, compute to $End_{\mathcal{B}}$ and store them in $L_1[End_{\mathcal{B}}]$.
3. For $\mathrm{DoF}_{\mathcal{R}}$ values of ■, compute to $End_{\mathcal{R}}$ and store them in $L_2[End_{\mathcal{R}}]$.
4. Find match between L_1 and L_2.
5. For the surviving pairs that pass the match, check for a full-state match.

Cplx.

According to $\lambda_{\mathcal{G}} = n - \lambda_{\mathcal{B}} - \lambda_{\mathcal{R}}$, then $\lambda_{\mathcal{G}} + l_{\mathcal{B}} + l_{\mathcal{R}} = n - \mathrm{DoF}_{\mathcal{B}} - \mathrm{DoF}_{\mathcal{R}}$,

$$
\begin{aligned}
T &= 2^{8\times(n-\mathrm{DoF}_{\mathcal{B}}-\mathrm{DoF}_{\mathcal{R}})} \times \left(2^{8\times\mathrm{DoF}_{\mathcal{B}}} + 2^{8\times\mathrm{DoF}_{\mathcal{R}}} + 2^{8\times(\mathrm{DoF}_{\mathcal{B}}+\mathrm{DoF}_{\mathcal{R}}-\mathrm{DoM})}\right) \\
&= 2^{8\times(n-\min\{\mathrm{DoF}_{\mathcal{B}},\mathrm{DoF}_{\mathcal{R}},\mathrm{DoM}\})} \\
M &= \min\{2^{8\times\mathrm{DoF}_{\mathcal{B}}},\ 2^{8\times\mathrm{DoF}_{\mathcal{R}}}\}
\end{aligned}
$$

Framework of the Meet-in-the-Middle Attack[EC:BDG+21]



1. ■ $\mathcal{R}$, $(x, y) = (0, 1)$: Known byte only with backward computation.
2. ■ $\mathcal{B}$, $(x, y) = (1, 0)$: Known byte only with forward computation.
3. ■ $\mathcal{G}$, $(x, y) = (1, 1)$: Constant byte and known in both forward and backward computations.
4. □ $\mathcal{W}$, $(x, y) = (0, 0)$: Unknown byte in forward and backward computations.

Enhanced Techniques[C:DHSLWH21]

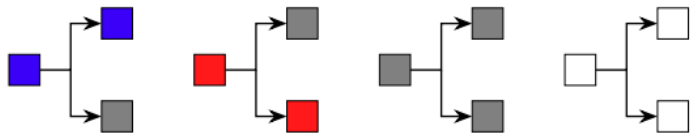
- Initial structure
  - Linear constraints: Solving linear systems of equations
  - Nonlinear constraints: Precomputing the concrete value of constraint constants $\mathfrak{c}_{\mathcal{B}}$ by traversing $\lambda_{\mathcal{B}}$ ■ and store $\mathrm{DoF}_{\mathcal{B}}$ ■ in table $U[\mathfrak{c}_{\mathcal{B}}]$. Similar to ■ and $V[\mathfrak{c}_{\mathcal{R}}]$.

Improved attack framework

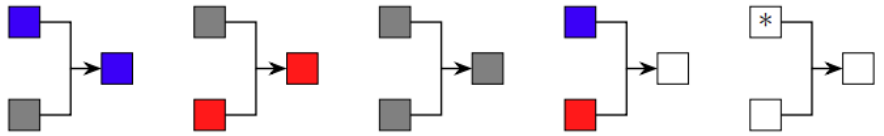
1. Choose constants for the starting states.
2. Build two table to solve nonlinear constraints $\mathfrak{c}_{\mathcal{B}}/\mathfrak{c}_{\mathcal{R}}$ with additional time $\max\{2^{8\times\lambda_{\mathcal{B}}},\ 2^{8\times\lambda_{\mathcal{R}}}\}$ and memory $\max\{2^{8\times\lambda_{\mathcal{B}}},\ 2^{8\times\lambda_{\mathcal{R}}}\}$.
3. For each $\mathfrak{c}_{\mathcal{B}}$, $\mathrm{DoF}_{\mathcal{B}}$ values of ■ are computed to $End_{\mathcal{B}}$ and store in $L_1[End_{\mathcal{B}}]$.
4. For each $\mathfrak{c}_{\mathcal{R}}$, $\mathrm{DoF}_{\mathcal{R}}$ values of ■ are computed to $End_{\mathcal{R}}$ and store in $L_2[End_{\mathcal{R}}]$.
5. Find match between L_1 and L_2.

Enhanced Techniques[C:BGST22]

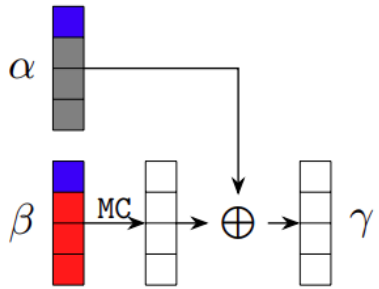
- Intermediate states are separated into two Superposition(SupP) states.
- SupP states are handled independently in linear operation and can be propagated equally in Bi-directions(BiDir).
- SupP states are combined before the next nonlinear operation.



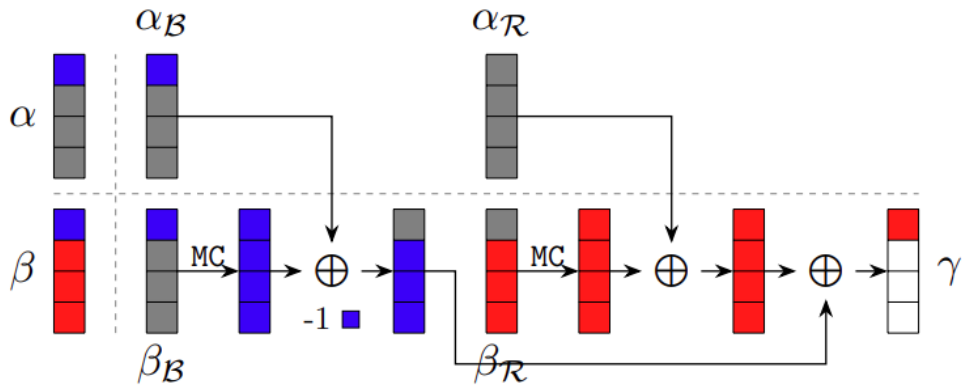
(a) Rules for separation



(b) Rules for combination



☒ MC and Xor



☑ SupP MC and Xor

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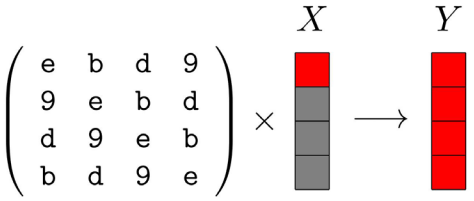
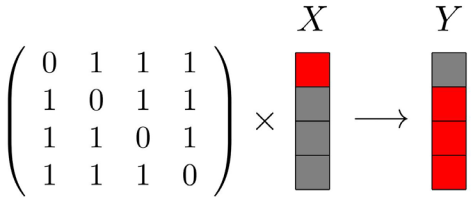
New models for linear layer with binary matrix

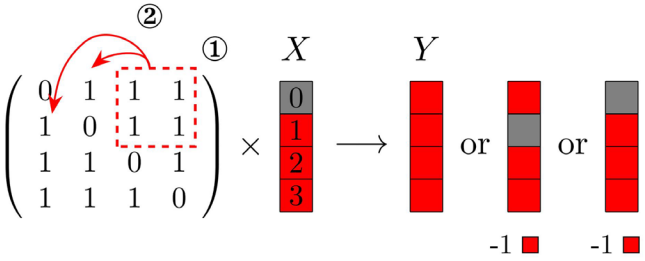
n-XOR Model



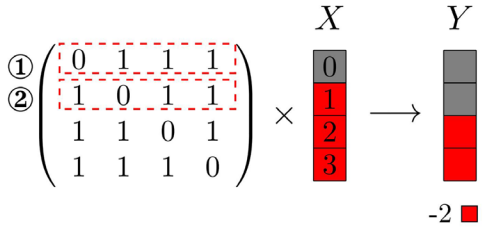
(a) Coloring pattern of `MC-RULE` for MDS matrix



(b) Coloring pattern for binary matrix



(a) Model of consecutive `XOR`



(b) `n-XOR` Model

n-XOR Model

- n-XOR-RULE^{-}-1. If there is at least one □ in input, then the output is □.
- n-XOR-RULE^{-}-2. If all cells of the input are ■, then the output must be ■.
- n-XOR-RULE^{-}-3. If there are ■ and ■ cells but no □ cell in the input, then one of the following situations will occur:
  - The output is ■ cell and no DoF is consumed.
  - The output is ■ by consuming one DoF of ■.

$$\begin{cases} \sum_{i=0}^{n-1} y_i^A + \mu \leq n \\ \sum_{i=0}^{n-1} y_i^A + n \cdot \mu \geq n \\ \sum_{i=0}^{n-1} x_i^A - \nu \leq n-1 \\ \sum_{i=0}^{n-1} x_i^A - n \cdot \nu \geq 0 \end{cases} \quad (2) \qquad \begin{cases} y^B + \mu = 1 \\ x^B + \mu \leq 1 \\ \eta - x^B + \nu = 0 \\ \sum_{i=0}^{n-1} x_i^A + x^B - 2 \cdot \nu \leq n-1 \\ \sum_{i=0}^{n-1} x_i^A + x^B - (n+1) \cdot \nu \geq 0 \end{cases} \quad (3)$$

Check Model: More Accurate Consumption of DoFs

$$\begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \times \begin{matrix} X \\ 0 \\ 1 \\ 2 \\ 3 \end{matrix} \longrightarrow \begin{matrix} Y \\ \\ \\ \\ \\ \end{matrix}$$

i.e. n-XOR Model $\begin{cases} X[1] \oplus X[3] = c_0 \\ X[1] \oplus X[3] = c_1 \end{cases}$ -2 ■

Check Model $\Longrightarrow$ $\begin{cases} X[1] \oplus X[3] = c_0 \\ X[1] \oplus X[3] = c_0 \end{cases}$ -1 ■

(a) Possible situation I

$$\begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \times \begin{matrix} X \\ 0 \\ 1 \\ 2 \\ 3 \end{matrix} \longrightarrow \begin{matrix} Y \\ \\ \\ \\ \\ \end{matrix}$$

i.e. n-XOR Model $\begin{cases} X[2] \oplus X[3] = c_0 \\ X[1] \oplus X[3] = c_1 \\ X[1] \oplus X[2] = c_2 \end{cases}$ -3 ■

Check Model $\Longrightarrow$ $\begin{cases} X[2] \oplus X[3] = c_0 \\ X[1] \oplus X[3] = c_1 \\ X[1] \oplus X[2] = c_0 \oplus c_1 \end{cases}$ -2 ■

(b) Possible situation II

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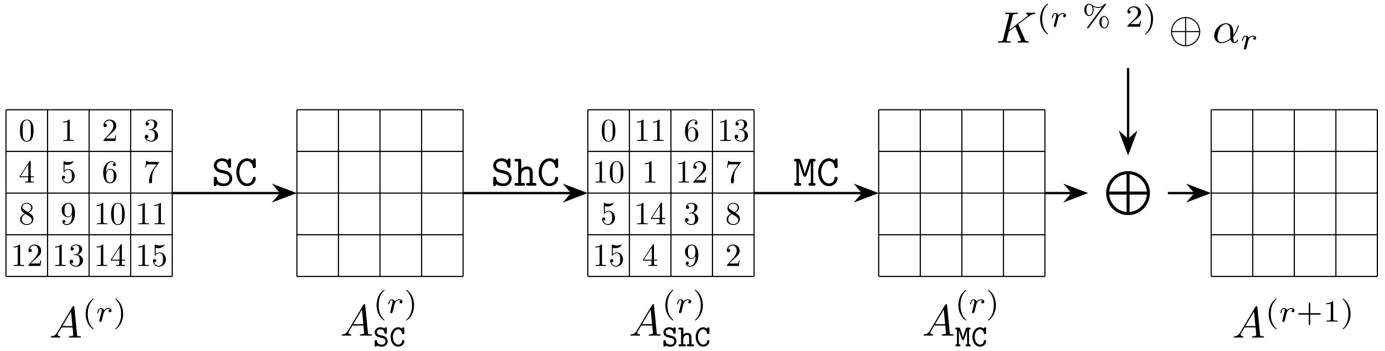
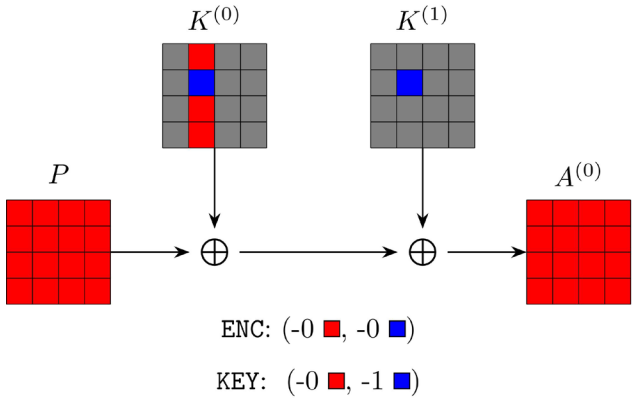
Key recovery attack on Midori64

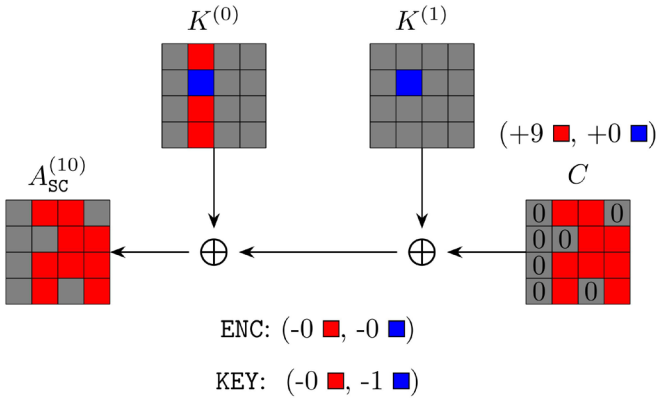
Key Recovery Attack on 11-round Midori64

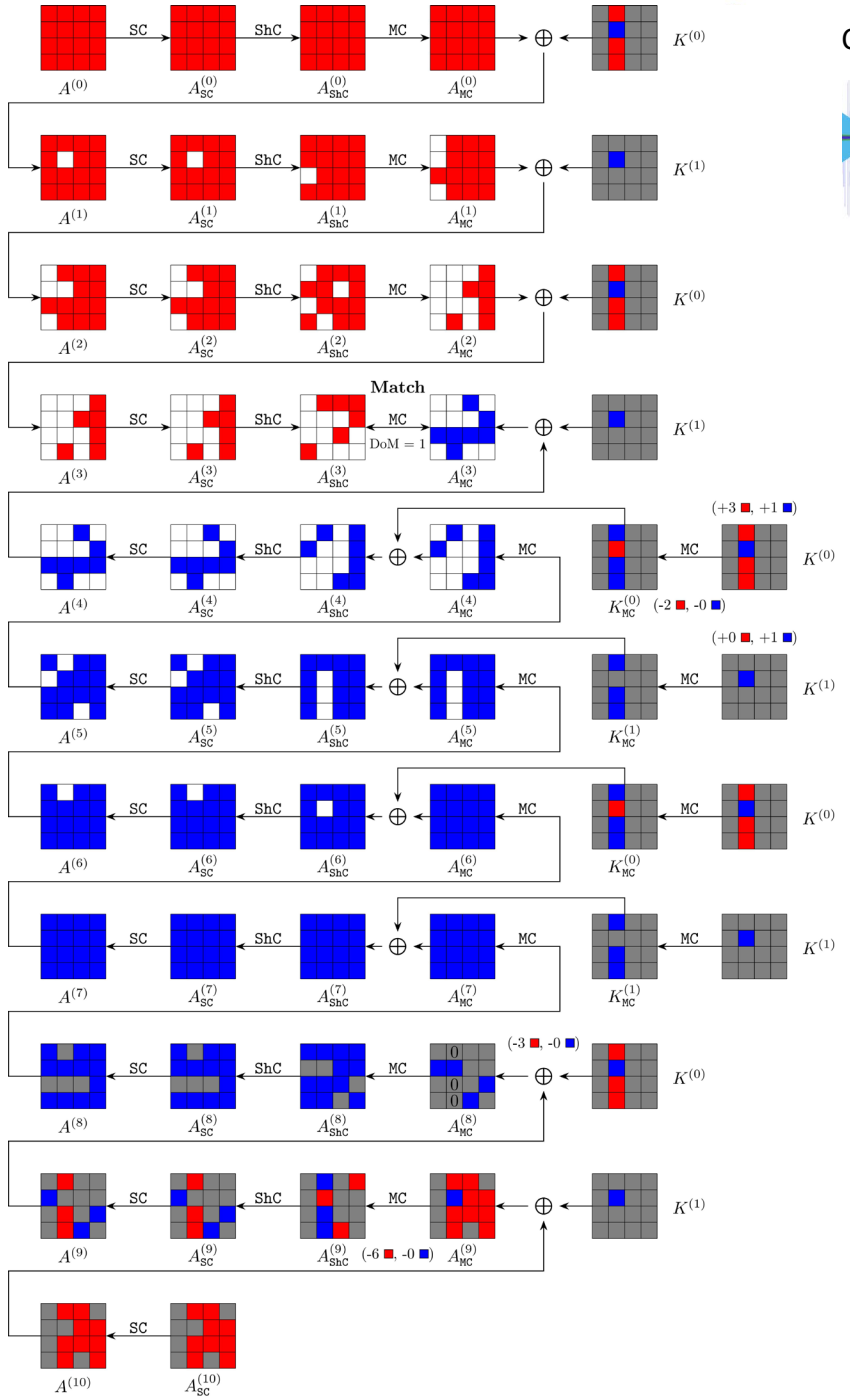


$$M = \begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix}.$$

Key Recovery Attack on 11-round Midori64







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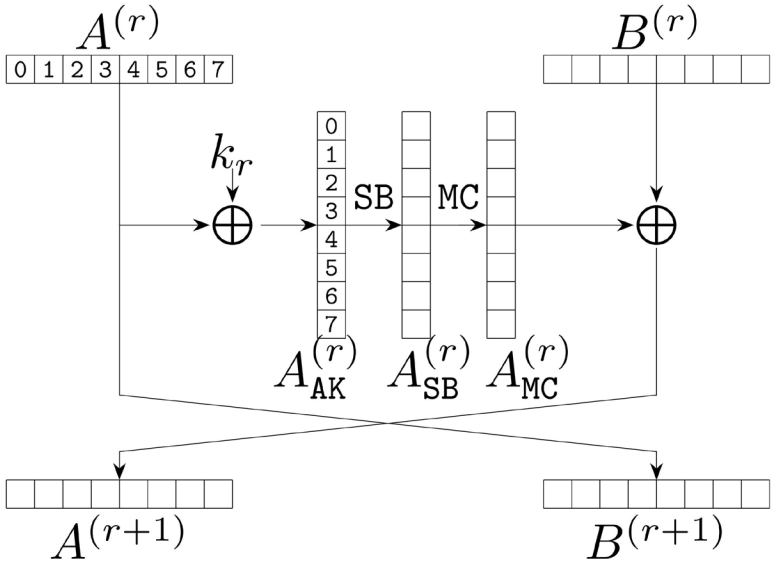
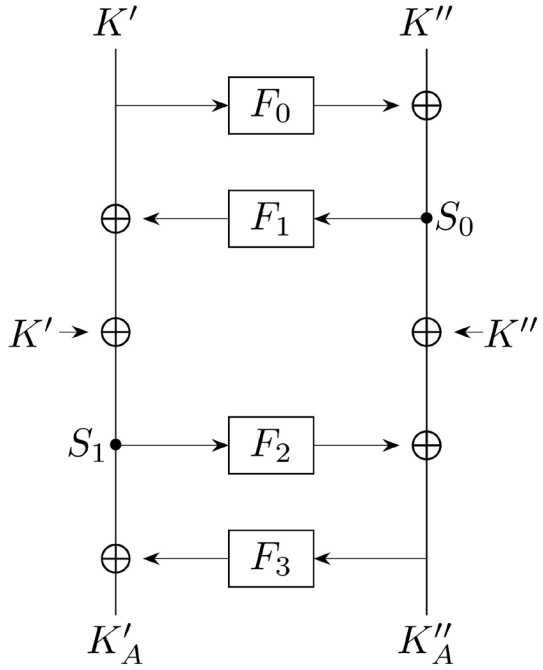
Preimage attack on weakened Camellia and Aria

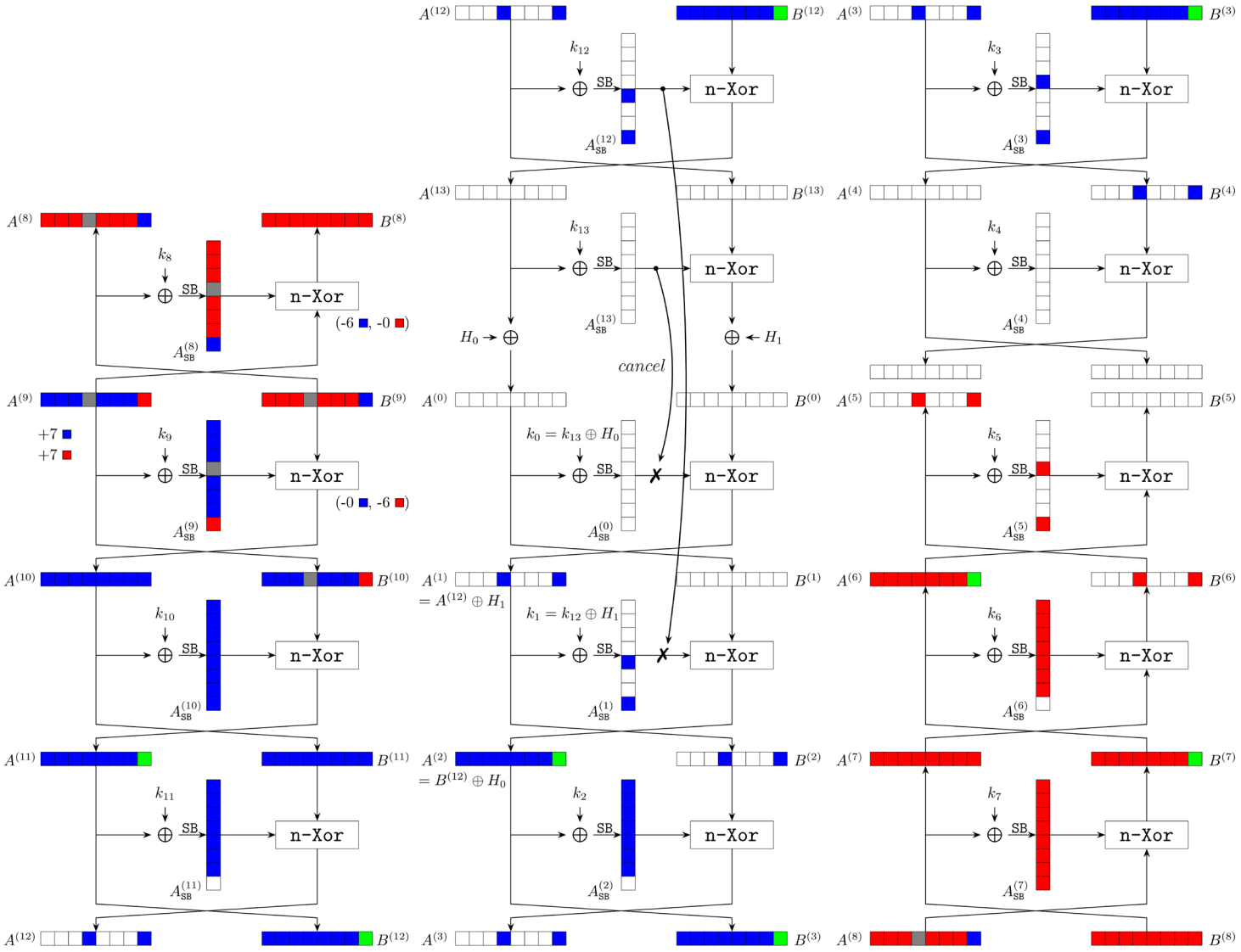
MitM Characteristic of 14-round weakened Camellia





$$P = \begin{pmatrix} 1\,0\,1\,1\,0\,1\,1\,1 \\ 1\,1\,0\,1\,1\,0\,1\,1 \\ 1\,1\,1\,0\,1\,1\,0\,1 \\ 0\,1\,1\,1\,1\,1\,1\,0 \\ 1\,1\,0\,0\,0\,1\,1\,1 \\ 0\,1\,1\,0\,1\,0\,1\,1 \\ 0\,0\,1\,1\,1\,1\,0\,1 \\ 1\,0\,0\,1\,1\,1\,1\,0 \end{pmatrix}.$$

MitM Characteristic of 14-round weakened Camellia



(a) Initial structure (b) 4-round shrink and link (c) Matching point

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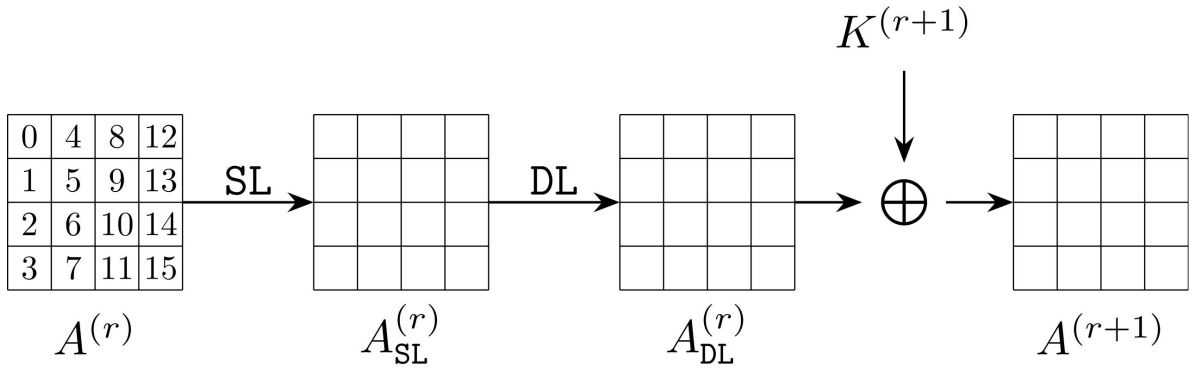
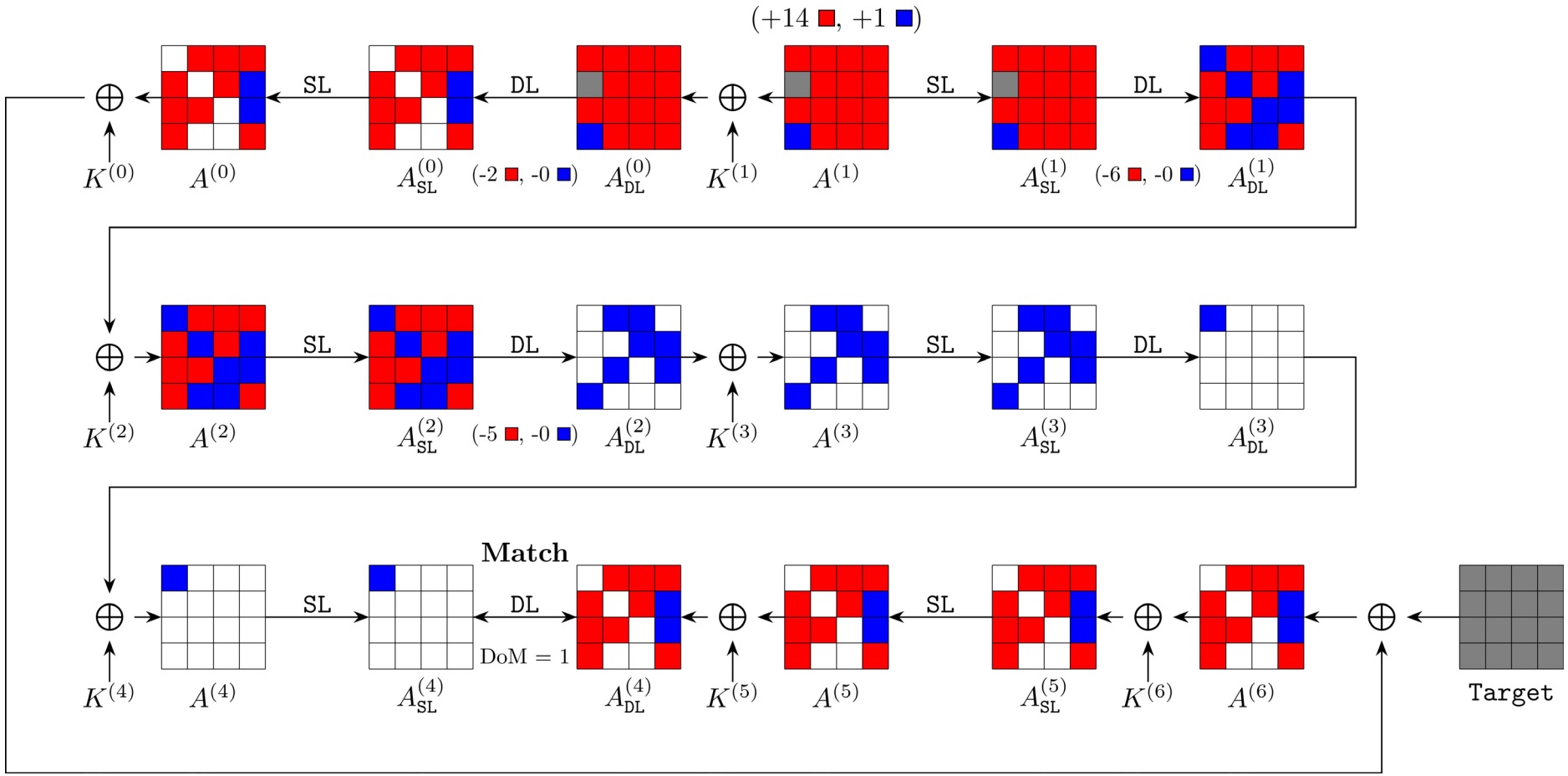
Preimage Attack on 6-Round Aria



$$P = \begin{pmatrix}
0&0&0&1&1&0&1&0&1&1&0&0&0&1&1&0\\
0&0&1&0&0&1&0&1&1&1&0&0&1&0&0&1\\
0&1&0&0&1&0&1&0&0&0&1&1&1&0&0&1\\
1&0&0&0&0&1&0&1&0&0&1&1&0&1&1&0\\
1&0&1&0&0&1&0&0&1&0&0&1&0&0&1&1\\
0&1&0&1&1&0&0&0&0&1&1&0&0&0&1&1\\
1&0&1&0&0&0&0&1&0&1&1&0&1&1&0&0\\
0&1&0&1&0&0&1&0&1&0&0&1&1&1&0&0\\
1&1&0&0&1&0&0&1&0&0&1&0&0&1&0&1\\
1&1&0&0&0&1&1&0&0&0&0&1&1&0&1&0\\
0&0&1&1&0&1&1&0&1&0&0&0&0&1&0&1\\
0&0&1&1&1&0&0&1&0&1&0&0&1&0&1&0\\
0&1&1&0&0&0&1&1&0&1&0&1&1&1&0&0\\
1&0&0&1&0&0&1&1&1&0&1&0&0&1&0&0\\
1&0&0&1&1&1&0&0&0&1&0&1&0&0&1&0\\
0&1&1&0&1&1&0&0&1&0&1&0&0&0&0&1
\end{pmatrix}.$$

Preimage Attack on 6-Round Aria



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Conclusion

Conclusion

Table 1: Single Key attacks on `Midori64`, where ID and $\mathcal{DS}$-MitM denote impossiable differential and Demirci-Selçuk MitM attack, respectively.

Target	Rounds	Data	Memory(Bytes)	Time(Enc.)	Technique	Ref.
`Midori64`	11	2^{60}	$2^{95.8}$	$2^{116.6}$	ID	[23]
	11	2^{53}	$2^{92.2}$	2^{122}	$\mathcal{DS}$-MitM	[22]
	11	$\mathbf{2^{36}}$	$\mathbf{2^{6}}$	2^{124}	MitM	Section 4.1
	12	$2^{55.5}$	2^{109}	$2^{125.5}$	$\mathcal{DS}$-MitM	[22]
	$12^{\dagger}$	$2^{61.9}$	2^{44}	$2^{90.5}$	ID	[35]
	$12^{\dagger}$	$\mathbf{2^{48}}$	$\mathbf{2^{10.6}}$	2^{120}	MitM	Section 4.2
	$12^{\dagger}$	$\mathbf{2^{36}}$	$\mathbf{2^{5.6}}$	2^{124}	MitM	Section 4.2

† Weakened version without whitening layers.

Table 2: A Summary of the MitM Attacks on Hashing Modes.

Target	Attacks	Rounds	Time1	Time2	Memory	Technique	Ref.
`Camellia-MMO`	Preimage	$13^{\ddagger}$	2^{120}	2^{125}	2^{8}	MitM	[28]
		$14^{\ddagger}$	2^{120}	2^{125}	2^{8}	MitM	Section 5
`Aria-DM`	Preimage	5	2^{120}	2^{125}	2^{8}	MitM	[16]
		6	2^{120}	2^{125}	2^{112}	MitM	Section 6

- ‡ Weakened version without FL/FL^{-1} and whitening layers.
- Time1 represents the time complexity of pseudo-preimage. Time2 represents the time complexity of preimage attack converted from the pseudo-preimage attack according to [24, Fact9.99].

Conclusion

- Propose the n-XOR model to simulate the XOR operation with an arbitrary number of input cells.
- Introduce another check model to determine the exact DoFs consumption of MitM attributes propagation, to liminate the subtle inaccuracies caused by n-XOR model
- Leading to improved MitM attack on Midori, Camellia, Aria
- Limitations: the size of the check model is still limited by the number of input cells n and does not work well when n > 4 in this paper.

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One Community.

Thank You

Full Version: https://eprint.iacr.org/2025/082

Source Code: https://github.com/wenny-kt/MITM-Binary-Matrix